AD616298

California Institute of Technology
Seismological Laboratory
Pasadena, California

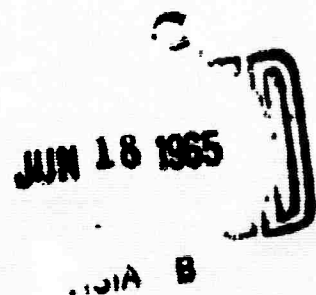# UPPER MANTLE STRUCTURE OF WESTERN NORTH AMERICA
FROM APPARENT VELOCITIES OF P WAVES

Mansour Niazi and Don L. Anderson

May 1965

ARPA Order No.:	292-63 Amendment No. 9
Project Code No.:	3810
Date of Contract	1 November 1963
Contract No.:	AF-49(638)-1337
Contract Termination Date:	31 October 1966
Project Scientist:	Dr. Frank Press, 795-8806
Project Title:	Research in Seismic Phenomena Connected with Earthquakes and Explosions

UPPER MANTLE STRUCTURE OF WESTERN NORTH AMERICA

FROM APPARENT VELOCITIES OF P WAVES[1]

MANSOUR NIAZI AND DON L. ANDERSON

Seismological Laboratory

California Institute of Tec nology, Pasadena

Abstract.   Variation of the compressional velocity with depth in the C-region of the upper mantle in western North America is studied. Apparent velocities of first arrivals across the Tonto Forest Array in Arizona has been determined for about 70 shallow focus earthquakes. The epicenters range from 10 to 30 degrees in distance and are mostly south of the array.

The method gives the slope of the travel time curve directly, the parameter required for a velocity-depth determination. For this distance range it is found that although the slope of the P travel time curve decreases sub-stantially with distance, i.e., increasing apparent velocity, the variation is not uniform. Two relatively abrupt changes are observed at distances of about 17 and 24 degrees. These are most readily interpreted as two second order dis-continuities in the region of the mantle above 1000 km.

Assuming an average crustal structure as derived from seismic refrac-tion measurements and taking the uppermost 200 km of the mantle given by Gutenberg or Jeffreys, various possibilities are explored for the form of variation of the P wave velocity with depth. The discontinuities in the rate of change of velocity with depth which cause the observed breaks in the apparent velocity curve are found to be at depths of about 320 and 640 km. Although no absolute times are required in the method the travel times for the various derived models are computed and compared with standard tables.

R-1

INTRODUCTION

The most abundant and direct source of data regarding the structure of the earth's interior is the travel time of various seismic body phases. The Herglotz-Wiechert method used in the interpretation of body waves requires a knowledge of $dt/d\Delta$ as a function of distance. This is ordinarily obtained from the slope of the observed travel time curve and involves the smoothing of observations made at seismic observatories with different crustal structures.

Application of this method has yielded a number of velocity-depth profiles which are similar except in the upper 1000 km of the mantle and a small region of the transition zone of the core. There are various reasons for the differences in the derived structures of the upper mantle including real variations, errors of apparent velocity introduced by smoothing of scattered data and disagreement in the interpretation of data. The existence or absence of low-velocity layers and discontinuities are the main differences between the standard models of Gutenberg, Lehman, and Jeffreys. These are also the complications which lead to theoretical difficulties in the body wave travel time method. The models of Gutenberg and Lehman have an upper mantle low-velocity region; Jeffrey's model does not. The models of Lehman and Jeffreys have a strong discontinuity above a depth of 400 km; Gutenberg's model is smooth throughout the mantle. The scatter of travel time data and the complicated amplitude pattern in the epicentral region of 15° to about 28° is partly responsible for the ambiguities of interpretation.

The first evidence for the sudden change of the slope of the travel time curve of P waves near the epicentral distance of 20 degrees was presented by Byerly (1926). In a later analysis of the Nevada earthquake of December 20, 1932 with considerably more data (Byerly, 1935) he noted that the P travel times

showed two discontinuities at epicentral distances of about 17 and 28 degrees, the latter being clearer. In the last few years, measurements have revealed additional evidence for discontinuities in the upper 1000 km of the mantle. A brief account of these observations is summarized by Anderson (1965) .

In recent years a number of seismometer arrays have been installed around the world, some having linear dimensions of several kilometers. The primary purpose of these installations is the improvement of signal to noise ratio to increase the capability of the detection of small events. Each array is pra. ically equivalent to several stations with essentially identical under- lying crust and having the same azimuth from the epicenter. They can, therefore, be used for direct measurement of $dt/d\Delta$ of various seismic phases.

The linear extent of an array which can be used for this purpose is restricted on one hand by the required resolution of the time of arrival of the signal, and on the other hand by the desired homogeneity of the underlying crust and upper mantle. While the latter restriction depends on the degree of lateral variation in the uppermost 50 to 100 km of the earth's structure, the former varies with the phase under consideration and with epicentral distance.

In this paper the seismograms of $_\wedge$shallow earthquakes, selected from among more than 200, and one underground explosion, recorded at Tonto Forest Seismological Observatory (TFSO), Arizona, are studied. The $dt/d\Delta$ of the first arrivals in the P group of these earthquakes across the array were measured and examined for possible indications of discontinuities in the region of the mantle between 225 and 800 kilometers depth.

Details of the installation and operation at TSFO are published in the semi-annual progress reports of the observatory. Data are read from the recordings of the short period vertical seismometers installed at the end points

of a crossed linear array (Z63, Z67, Z70 and Z74 in Figure 1). The array

consists of two perpendicular lines, each of which is approximately 10 km long

and contains eleven seismometers. The instruments are of the Johnson-Matheson

type, running with unusually high magnification of 650 K at 1 cps.

In Figure 2, the recordings of first P arrivals of two of the earth-

quakes are reproduced. The first earthquake has a magnitude of 5.4 and is

located 13.3 degrees toward the northwest of the array. The second one has an

epicentral distance of 20.3 degrees to the southeast of TSFO and a magnitude

of 4.1. The clear later arrivals are an additional source of information regarding

structure of the upper mantle which we do not use in the present paper because

of uncertainties in the depths of the sources.

ANALYSIS OF DATA

A list of the data is given in Table 1. All but the numbers listed

in the last column are reproduced from the Geotech monthly bulletins, and are

based on the USCGS preliminary reports. The measured slopes are given in the

last column. Only two of the earthquakes have listed focal depthsof over 50 km

for which   appropriate correctionsin the epicentral distances are made.

The distribution of the epicenters around TSFO is exhibited in Figure 1.

The epicentral distances range from 12 to 28 degrees. About twenty per cent

of the azimuths are to the northwest; the remaining 80 per cent stretch from due

south to the southeast of TSFO.

A plot of the measured slopes is shown in Figure 3. Solid circles

represent earthquakes located to the northwest of TFSO. The azimuths of the earth-

quakes shown by the hollow circles range from due south to the southeast. The

point marked by $\triangle$ belongs to the Salmon underground explosion in Mississippi

($\triangle = 18.5^o$, Az = 93.7^o). For this explosion the slope was measured on the

horizontal components.

In the same figure the tabulated Jeffreys slopes $dT/d\Delta$ for shallow earthquakes (h=0.00 R), computed from the Jeffreys-Bullen tables (1958) are smoothed and shown by the dashed line. It is noted that a variation of slopes such as the one given by the Jeffreys model is not in close agreement with our measured values. Our data fails to indicate any sudden decrease in $dT/d\Delta$ at Δ = 20°. Instead, there are indications that the assumed discontinuity at this distance is the compounded effect of the gradual decrease of the slope in the spicentral range between 15 and 25 degrees which may include two less pronounced discontinuities at epicentral distances of about 17 and 24 degrees.

Evidence for the existence of twin discontinuities with close correspondence to the ones suggested here have previously been presented by a number of investigators (see, for example, Doyle and Webb, 1963). With the commonly used technique of few observations several degrees apart, it is extremely difficult to see the fine structure of the travel time curve. Furthermore, when the observed points are substituted by straight lines the information concerning small abnormalities are lost.

The data presented in Figure 3, though illustrating the general trend, is quite scattered. This is in particular true for distances less than 15 degrees. Most of the earthquakes in this range are from off the coast of northern California and Oregon (solid circles). Paths of these earthquakes traverse the anomalous region underlying the Sierra Mountains. Also some scattering arises from the fact that P_n may still appear as the first arrival. Miss Lehman (1964) observed that P_n to the northeast of the Gnome explosion was a first arrival to epicentral distances as far as 19 degrees. The P_n velocity also varies rather rapidly in different regions of the western United States. Large amplitude later arrivals may also have been picked as first arrivals.

Other factors contributing to the scattering are errors in measure-- ments and uncertainty in the epicentral distances. By analyzing only superior seismograms with low background noise and prominent first arrivals we attempted to minimize reading errors. Nevertheless, such errors may result in uncertainties as large as 1.0 sec/deg in the measured slopes. More accurate location, on the other hand, requires an even distribution of recording st'tions around the epicenter. This is not realized for the earthquakes under consideration, because of their geographic location. A study of this nature, therefore, should include a large number of observations so that a statistical treatment of the data becomes possible.

Two alternate methods were adopted to smooth the data prior to interpre- tation. In the first method all the observations were fitted by a single least square polynomial of degree 9, giving a standard error of estimate of 0.43 sec/deg. In the second method the data were treated in three groups with breaks at distances of 17 and 24 degrees. Each group was fitted by a polynomial of degree 5. The standard error of estimate for the whole range in the latter case is reduced to 0.35 sec/deg. The discontinuous solid curve in Figure 3 resulted from the second procedure.

Due to the uncertainty in the nature of the first arrivals and high scattering of the data at distances less than 15 degrees we made use of two well established models for depths corresponding to this epicentral range. The uppermost 200 km of the mantle is alternately assumed to have P velocities suggested by Jeffreys (see Bullen, (1963) and Gutenberg (1959)). Based on the preliminary results of recent seismic refraction work in the recording region (Warren et al, 1965), a single layered crust of 30 km thickness, having an average compressional velocity of 6.1 km/sec is also assumed.

Under these assumptions and a choice of continuous or discontinuous treatment of the data, a number of possible velocity-depth profiles are derived for depths up to 800 km. The method of successive stripping is applied so that prior to the application of the Herglotz-Wichert formulas

$$\ln (r_o / r_1) = (1/\pi) \int_0^{\Delta_1} \cosh^{-1} (p / p_1) \, d\Delta \quad ; \quad v_1 / r_1 = V / r_o$$

the parameters involved i.e., Δ , r_o and r_1 are properly reduced to those of the stripped earth. Here r_o is the radius of the earth, p parameter of the ray (equivalent to the slope of travel time curve), v_1 velocity at the bottom of the ray ($r=r_1$) emerging at an epicentral distance Δ_1 and having parameter p_1. V is the apparent surface velocity at distance Δ .

All the computations were performed on an IBM 7094 computer, and results are summarized in Table 2. A comparison of the variation of P velocity in the uppermost 800 km of the mantle derived here and those suggested by Jeffreys and Gutenberg is illustrated in Figure 4. Models X and Y are constructed on the basis of the hypothesis of gradual decrease of $dt/d\Delta$ in the epicentral range of 15 to 30 degrees and differ in the assumed structures between M-discontinuity and 225 km depth. In this interval X coincides with the Jeffreys model while Y with that of Gutenberg. Model Z also has a Gutenberg upper mantle, but the velocities between depths of 225 and 800 km are based on a $dt/d\Delta$ curve which has two discontinuities at distances of 17 and 24 degrees. The depths corresponding to these discontinuities are close to 320 and 640 km.

DISCUSSION OF RESULTS

As is apparent in Figure 4, all three models begin as the continuation of either Jeffreys or Gutenberg upper mantle (according to the assumptions made in the previous section) from a depth of about 225 km. For a good portion of the

profile, models X and Y represent an average to the Jeffreys and Gutenberg velocities and together with model Z converge to a value which is higher by about 0.2 km/sec at a depth of 800 km.

In the sectional smoothing of the data, one point at the epicentral distance of 15.9 degrees, for which the observed $dt/d\Delta$ is 12.9 sec/deg, has been assumed to be a second arrival and is thus combined with the observations between 17 and 24 degrees (see Figure 3). There is some arbitrariness in the way different portions of the curve meet. The accuracy of the present data is insufficient for deciding whether each portion continues along the dash-dot tail to join the adjacent portion smoothly, or there is some overlapping. Clear later arrivals on some of the records suggest that the travel-time curve is multi-valued.

For the sake of computational convenience, it is here assumed that the neighboring sections of the discontinuous curve slightly overlap. The corresponding jumps in the velocity profile are quite small (0.03 and 0.06 km/sec at 320 and 640 km depths, respectively), and, in the absence of other evidence such as reflections from such first order discontinuities, may be ignored. In sketching Figure 4, we have taken the resulting two discontinuities of model Z to be of second order.

Any suggested earth model should obviously satisfy the observed travel times. The three models resulting from this study are based on measurements of $dt/d\Delta$, without direct reference to the absolute values of the transmission time. Indirectly, however, the computed distances have been influenced by the selection of a set of travel time curves. The bias introduced by such procedure is not expected to be more serious than other sources of error which exist in the evaluation of distances. Furthermore, with less scattered data, it is possible to remove such bias by a process of successive approximation.

To examine the compatibility of the models with the travel times which are in common use, we have computed the variation of the transmission time with

distance of these models for a focal depth of 33 km (see Anderson and Julian. 1965). A comparison of the results of the computed time of first arrivals and JB tables is made in Figure 5. The initial values of the residuals (at $\angle$ =15°) can be explained by the difference in the crustal structures and also that between Gutenberg and Jeffreys upper mantles (for models Y and Z).

It can be seen from Figure 5 that models X and Z are in better agreement with JB tables than model Y. The residuals for model Y remain positive throughout the distance range under consideration and attain a maximum value of 3.3 seconds at Δ = 23.5 degrees. The residuals of the other two models include both positive and negative values. The most conspicuous positive range, common in all three models, is at distances between about 21 to 28 degrees. Such positive anomalies based on various assumptions can be interpreted to indicate that for this region the JB travel times should be slightly (at least one and possibly up to two seconds) increased in this distance range. A comparison between the residuals of models Y and Z, both of which have a Gutenberg upper mantle, indicates a preference for a discontinuous $dt/d\Delta$ variation, such as the one used to construct model Z, over a continuous one.

From Δ = 28° on the residuals of X and Z become negative. Such a decrease, in all three models, is due to high P velocities at depths near 800 km found here.

UNIQUENESS

Although we feel that the direct measurement and analysis of apparent velocity data is superior to the usual method of smoothing and differentiating travel-time data, particularly for the elucidation of fine structural details, there still remains a great deal of arbitrariness in the interpretation. In addition to the complications mentioned previously there is the possibility that the three regions of the P wave arrival data which we infer between 10 and 30

degrees are three separate branches which continue into the adjacent regions as later arrivals, perhaps even coalescing to form cusps. Without using later arrivals and amplitude data it is impossible to discuss the sharpness of the discontinuities. While the gradient of velocity in each depth region is probably determined correctly, limited only by the scatter of the data, the details of the transition regions are not resolved.

Our method of analysis can be considered to give the smoothest variation of velocity consistent with our tri-partite $d\tau/d\Delta$ curve. The model CIT11 (Anderson and Toksöz, 1963 ; Anderson, 1965) also has two major discontinuities at depths close to those determined here. Since this model was determined from surface waves it is stepped rather than smooth and represents probably the coarsest variation of velocity consistent with surface wave data. The actual nature of the discontinuities probably lies between these two extremes. The CIT11 model predicts multi-valued travel-time curves over most of the interval between 14 and 38 degrees. Model Z has only minor later arriving branches. Since we cannot distinguish between these two kinds of models on the basis of first arrivals alone we content ourselves here with a few numerical experiments, mainly to study the effect of the sharpness of the discontinuity. In Figure 6 we show model Z and two additional models. CIT11CS3 is a smoothed version of CIT11. Model Z1 is a more abrupt version of model Z. Both differ from model Z primarily in the location and abruptness of the discontinuities. Neither are designed specifically to satisfy our present data but merely to illustrate the difficulty of interpretation when discontinuities are present. Figure 7 gives the computed $d\tau/d\Delta$ for these three models. Clearly, later arrivals must be used to discuss details of transition zones.

TABLE 1

Date		O.T. h:m	Δ (°)	Az (°)	h (km)	M	$d\bar{t}/d\Delta$ sec/deg
1963							
Oct	4	08:34	22.3	141	41	4.5	10.9
	7	05:35	14.6	172	33	4.7	13.0
	11	09:51	17.0	161	33	4.6	12.3
	13	16:45	14.4	SE	50	4.8	11.7
	19	01:04	24.1	SSE	34	4.3	8.8
	29	07:01	12.3	NW	38	4.7	13.8
Nov	14	09:05	24.7	136	33	4.9	9.0
	20	01:13	23.5	330	39	4.0	10.2
Dec	3	12:23	17.0	160	33	4.0	11.9
	4	04:18	15.0	169	33	4.8	13.8
	12	00:38	16.0	165	33	4.5	13.0
	15	16:54	21.7	142	35	4.2	11.2
	22	01:20	25.8	136	33	4.4	9.1
	25	23:02	15.5	170	33	3.7	13.7
	28	06:57	26.2	134	33	4.5	9.4
	29	04:34	15.9	161	33	3.8	11.9
		06:22	16.3	161	33	4.4	13.8
	31	21:41	20.7	145	33	4.3	11.1
1964							
Jan	1	09:43	16.7	162	33	4.4	13.0
		19:45	12.2	156	33	4.0	13.8
	6	23:37	15.2	169	33	4.1	13.8
	11	00:40	21.3	144	33	4.5	10.7
	17	22:18	20.9	144	33	4.2	11.1
	18	14:40	24.5	137	33	4.6	9.4

Date	O.T.	$\triangle$	Az	h	M	$dt/d\triangle$
	h: m	(°)	(°)	(km)		sec/deg
1964						
Jan 20	20:30	20.8	143	33	4.3	11.1
23	01:42	16.1	167	33	3.8	13.4
28	04:56	14.5	313	17	4.5	14.2
31	17:07	19.6	334	14	4.2	11.1
Feb 3	02:00	26.0	137	34	4.3	9.1
	17:34	20.3	144	33	4.1	10.8
8	09:59	26.8	133	33	4.1	8.8
9	10:49	28.9	134	33	3.9	8.3
13	02:22	26.6	160	33	4.6	8.9
	02:30	26.8	161	33	4.7	8.4
	02:39	27.4	162	33	4.2	8.5
14	12:07	14.7	313	33	4.5	13.5
18	09:07	26.1	161	33	4.0	9.3
20	12:03	25.7	136	49	4.4	9.2
21	03:15	25.4	134	33	3.8	8.8
26	20:32	12.1	303	27	4.6	15.1
27	11:35	16.6	155	33	4.5	12.9
Mar 3	07:04	16.3	311	33	4.3	12.4
	20:02	12.5	303	33	4.8	14.5
5	11:42	12.2	299	33	4.3	14.3
8	19:12	14.2	158	33	4.1	14.4
	19:44	14.0	156	33	4.0	14.3
10	09:04	15.2	170	33	4.3	13.8
12	18:35	14.3	171	33	3.9	13.4
13	11:54	28.5	133	128	4.9	8.8

Date		O.T.	$\triangle$	Az	h	M	$d\dagger/d\triangle$
		h m	(^{o})	(^{o})	(km)		sec/deg
1964							
Mar	13	21:08	27.0	132	33	4.8	8.2
	18	11:39	26.1	134	31	4.0	9.4
	23	06:12	18.6	161	33	4.0	11.6
	24	09:37	21.4	327	22	4.2	10.6
	28	10:08	11.5	38	16	5.1	14.0
April	3	05:56	24.4	136	33	4.2	9.4
	8	03:38	23.4	317	33	4.3	9.8
June	3	11:41	15.0	169	33	4.1	13.7
		13:50	13.3	301	33	5.4	14.7
	4	04:28	19.2	148	22	4.7	10.9
	20	17:12	16.5	160	28	5.5	13.0
		19:35	16.3	160	33	4.5	13.0
	24	15:13	19.5	147	33	4.4	11.6
July	6	07:22	18.6	146	100	6.3	11.3
	14	12:47	13.6	308	33	5.4	14.6
	20	18:49	14.6	172	33	5.1	13.0
	21	01:07	14.8	172	33	5.3	13.4
		03:41	15.5	173	33	3.7	13.2
Aug	13	06:35	14.1	309	33	4.9	14.0
		08:50	13.7	310	33	4.9	14.0
Oct	22	Salmon	18.5	94			11.9

TABLE 2

(km/sec)

depth (km)	Jeffreys	X	Gutenberg	Y	Z
0	6.1	6.1	6.1	6.1	6.1
30	6.1	6.1	6.1	6.1	6.1
30	7.75		8.08		
60	7.84		7.87		
100	7.95		7.83		
160	8.13		8.00		
200	8.26		8.12		
225	8.34		8.18		
240		8.38		8.24	8.25
260		8.44		8.33	8.32
280		8.52		8.41	8.42
300	8.58	8.60	8.51	8.50	8.53
320		8.68		8.59	8.64
340		8.77		8.68	8.83
360		8.86		8.78	8.94
380		8.96		8.88	9.04
400	8.90	9.05	9.00	8.98	9.13
420		9.15		9.08	9.21
440		9.25		9.18	9.29
460		9.35		9.29	9.38
480		9.45		9.40	9.46
500		9.55	9.49	9.50	9.55
520		9.66		9.61	9.65

(km/sec)

depth (km)	Jeffreys	X	Gutenberg	Y	Z
540	9.91	9.77		9.73	9.74
560		9.87		9.84	9.84
580		9.98		9.95	9.94
600	10.25	10.09	9.99	10.06	10.05
620		10.20		10.18	10.16
640		10.31		10.29	10.28
660		10.42		10.41	10.50
680		10.54		10.52	10.62
700		10.65		10.63	10.74
720		10.76		10.75	10.85
740		10.88		10.86	10.95
760		10.99		10.97	11.05
780		11.10		11.07	11.14
800	11.00	11.21	11.00	11.18	11.24

REFERENCES

Anderson, D. L., Recent evidence concerning the structure and composition of the earth's mantle, Physics and Chemistry of the Earth, 6, 1-131, 1965.

Anderson, D. L., and B. R. Julian, Travel times, velocities and amplitudes of body phases (abstract), presented at the annual meeting of Seismol. Soc. Am., St. Louis, April 1965.

Anderson, D. L., and M. N. Toksüz, Surface waves on a spherical earth, 1, Upper mantle structure from Love waves, J. Geophys. Res., 68, 3483-3499, 1963

Bullen, K. E., An Introduction to the Theory of Seismology, Cambridge Press, p. 223, 1963.

Byerly, P., The Montana earthquake of June 28, 1925, Bull. Seismol. Soc. Am., 16, 209-265, 1926.

Byerly, P., The first preliminary waves of the Nevada earthquake of December 20, 1932, Bull. Seismol. Soc. Am., 25, 62-80, 1935.

Doyle, H. A. and J. P. Webb, Travel times to Australian stations from Pacific nuclear explosions in 1958, J. Geophys. Res., 68, 1115-1120, 1963.

Jeffreys, H. and K. E. Bullen, Seismological Tables, British Assoc. for the Advancement of Science, pp. 50, 1958.

Gutenberg, B., The asthenosphere low-velocity layer, Annali di Geofisica, 12, 439-460, 1959.

Lehman, I., On the travel times of P as determined from nuclear explosion, Bull. Seismol. Soc. Am., 54, 123-139, 1964.

Warren, D. H., J. C. Roller, and W. H. Jackson, A seismic-refraction survey in the vicinity of the Tonto Forest Seismological Observatory, Arizona (abstract), Trans. Am. Geophys. Union, 46, 155, 1965.

FIGURE CAPTIONS

Figure 1   Location of epicenters and array. Insert shows the geometry
            and orientation of the array.

Figure 2   Representative seismograms.

Figure 3   Apparent reciprocal velocity versus distance. Velocity
            model Z is based on the segmented curve. The dashed
            curve is for the Jeffreys-Bullen model.

Figure 4   Standard velocity-depth curves and three structures
            determined in this paper.

Figure 5   Travel-time residuals from the J. B. tables for the three
            new velocity structures.

Figure 6   Model Z and two other hypothetical mantle models.

Figure 7   Theoretical apparent reciprocal velocity curves for the
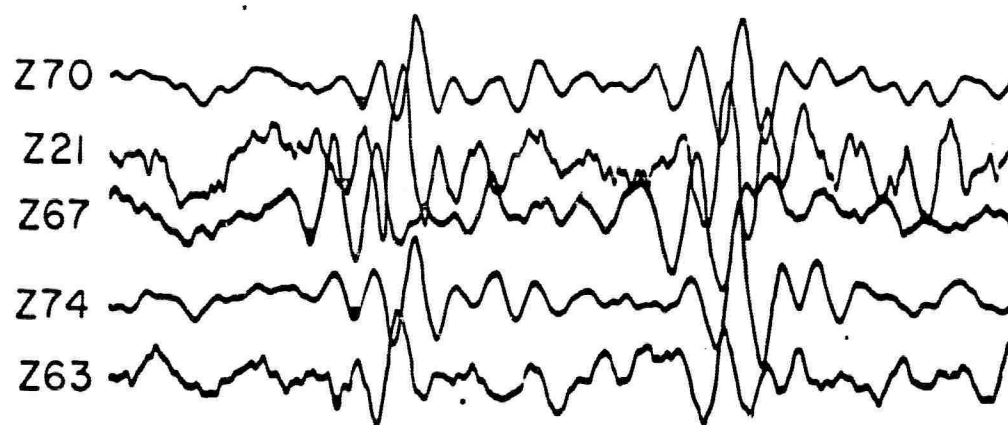   models shown in Figure 6.

CROSSED LINEAR ARRAY

0   10,000 ft.

Z74

Z70

Z 21

Z63

Z67

TFSO
X
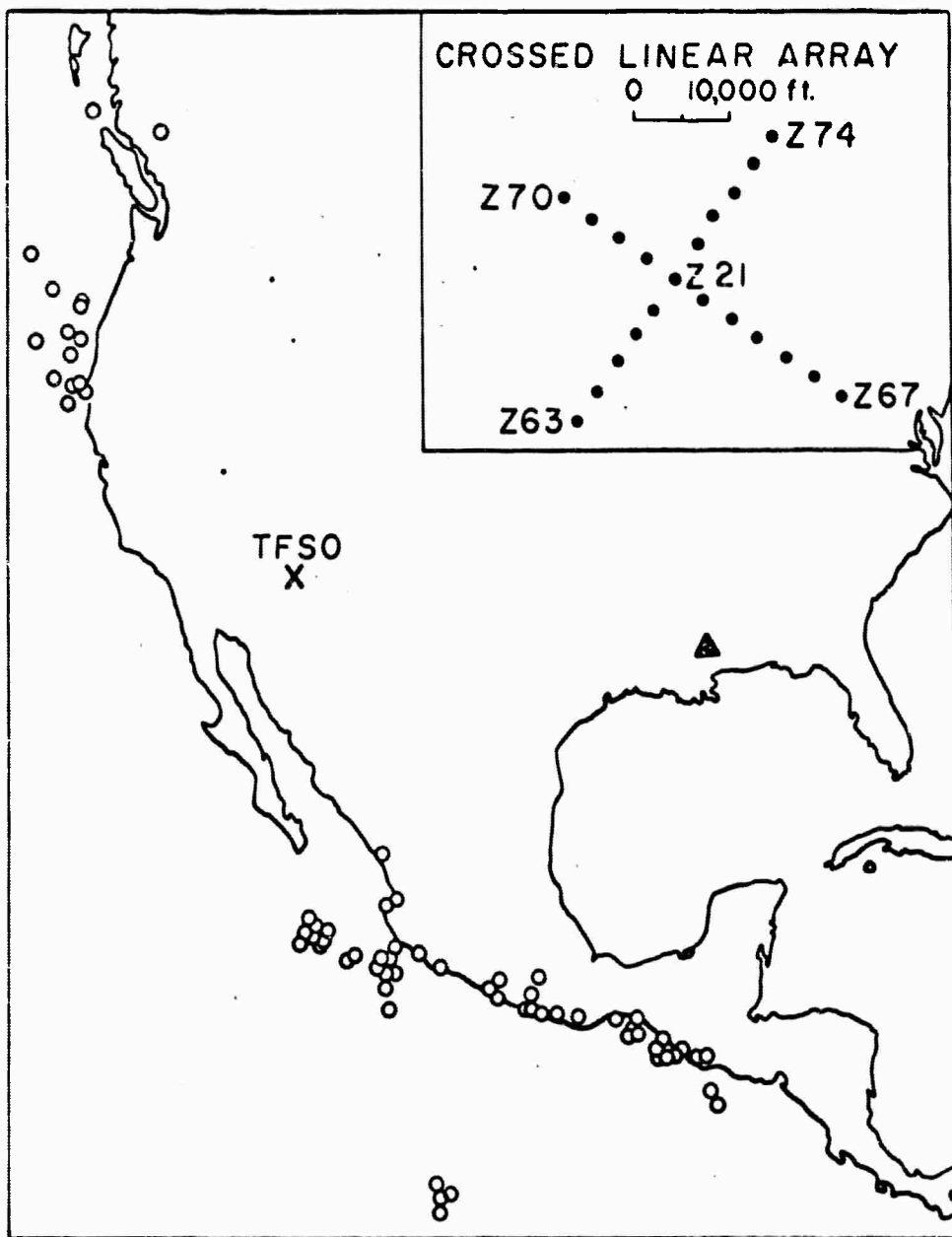
Fig. 1
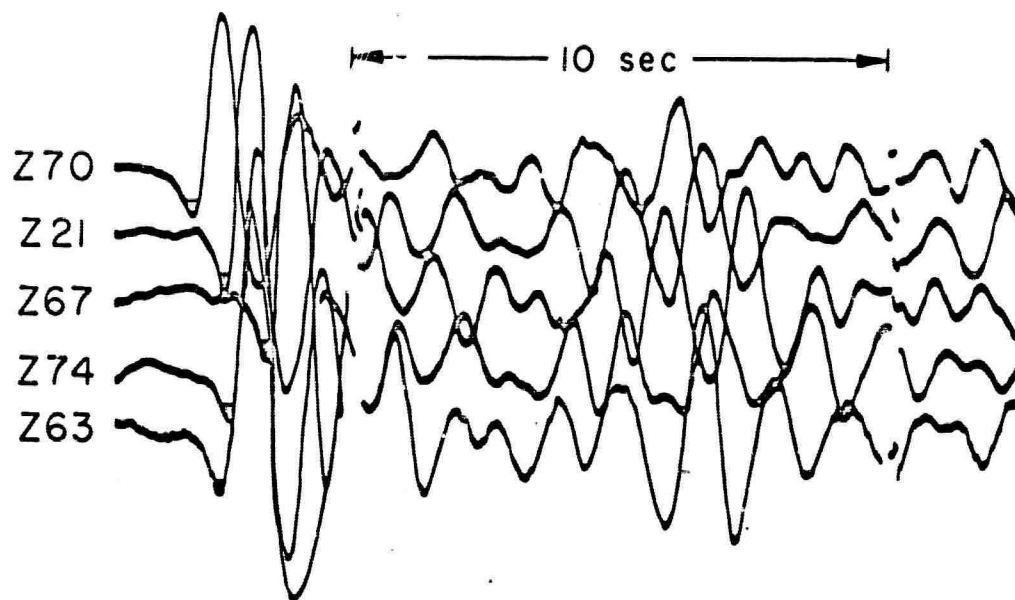
June 3, 1964, $\Delta = 13.3°$, $\phi = 301°$

Feb. 3, 1964, $\Delta = 20.3°$, $\phi = 144°$

Fig. 2

Fig. 3

Fig. 4

The figure is a plot of Velocity, km/sec (y-axis, ranging from about 8 to 11) versus Depth, km (x-axis, ranging from 0 to 800). A legend table within the plot reads:

Model	Depth, km	
	Moho–225	225–800
X	Jeffreys	Continuous
Y	Gutenberg	Continuous
Z	Gutenberg	Discont.

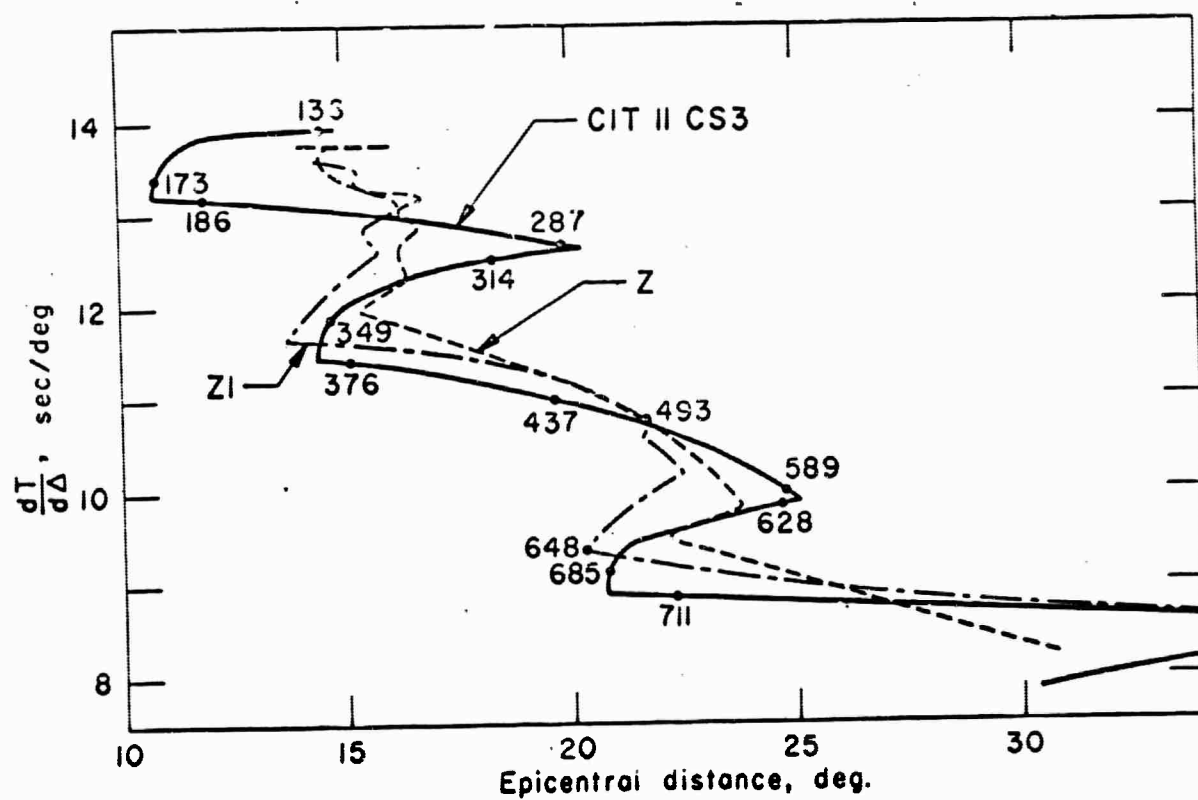Curves are labeled X, Y, Z, Jeffreys, and Gutenberg.
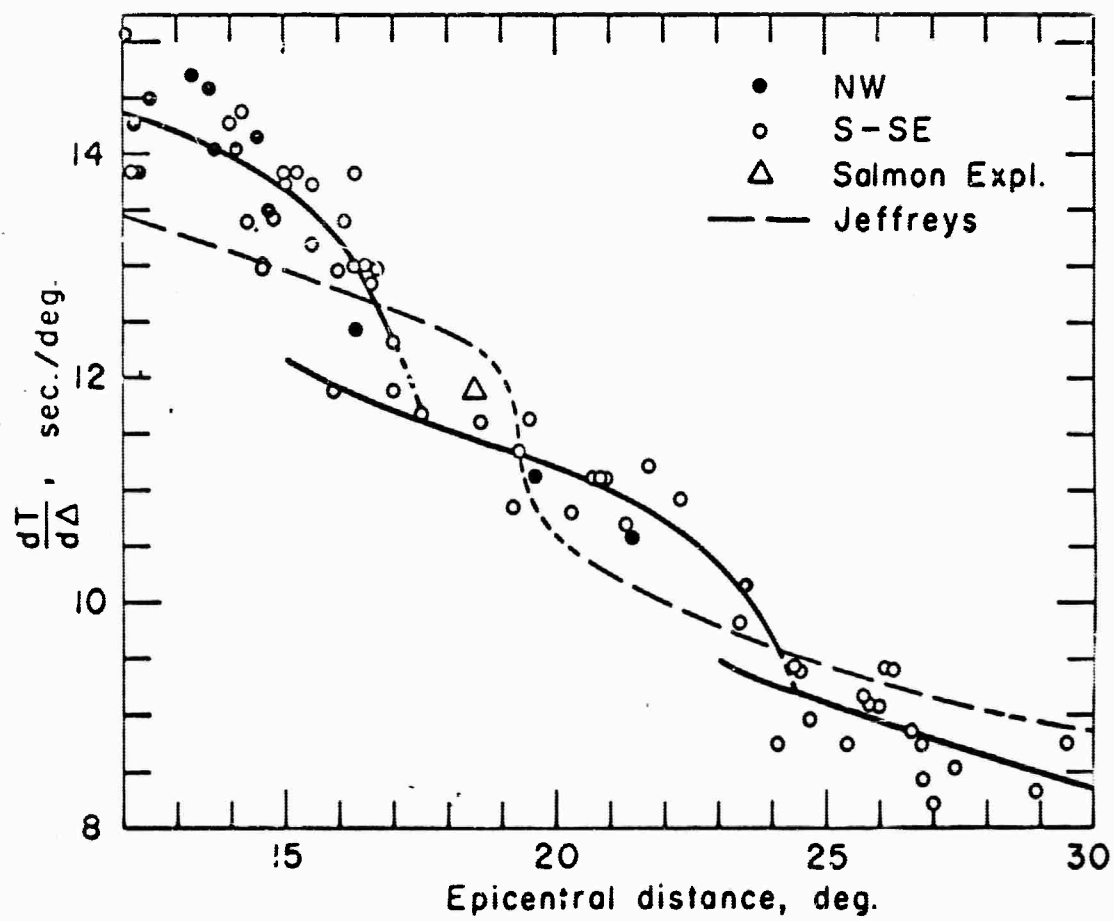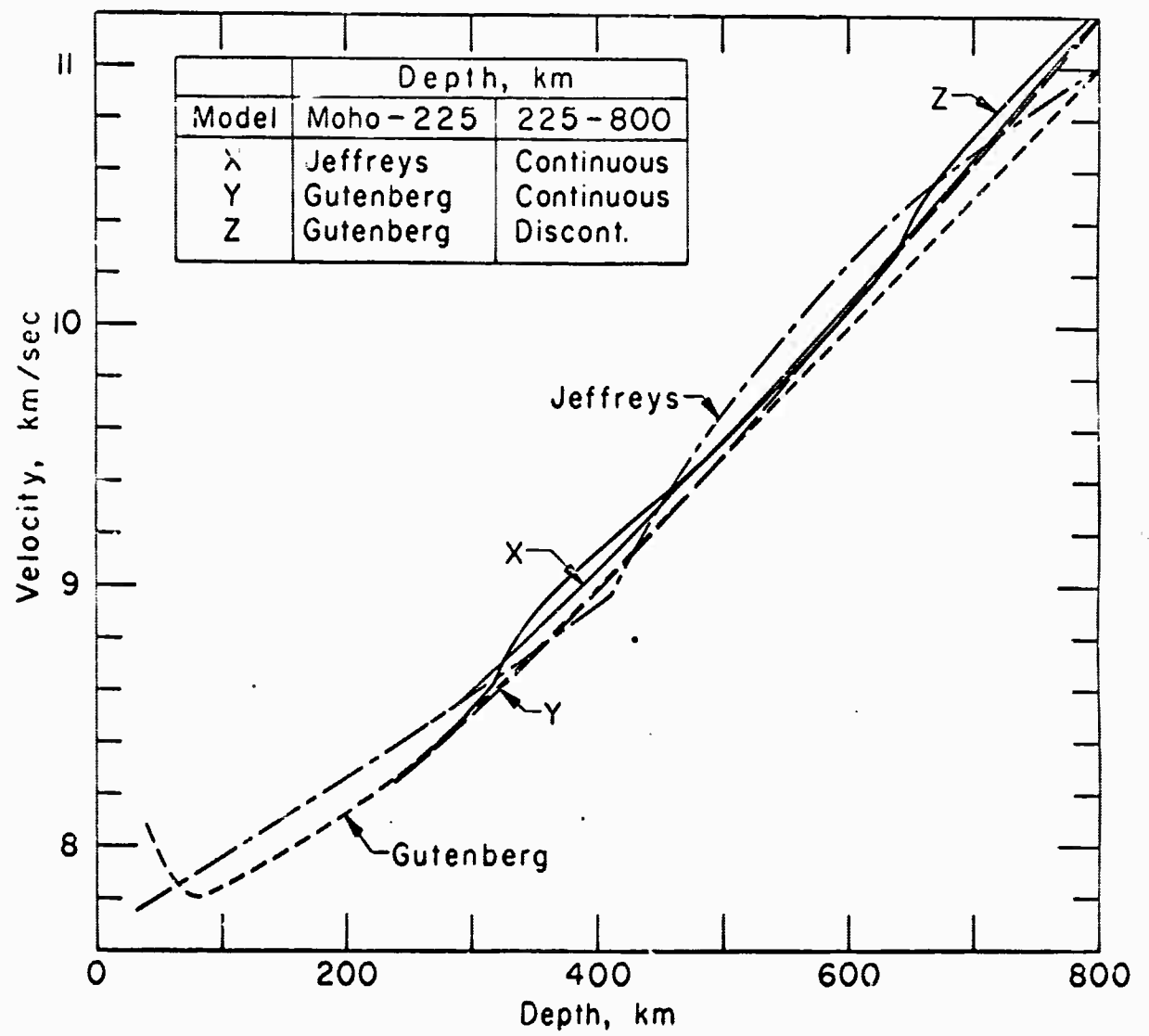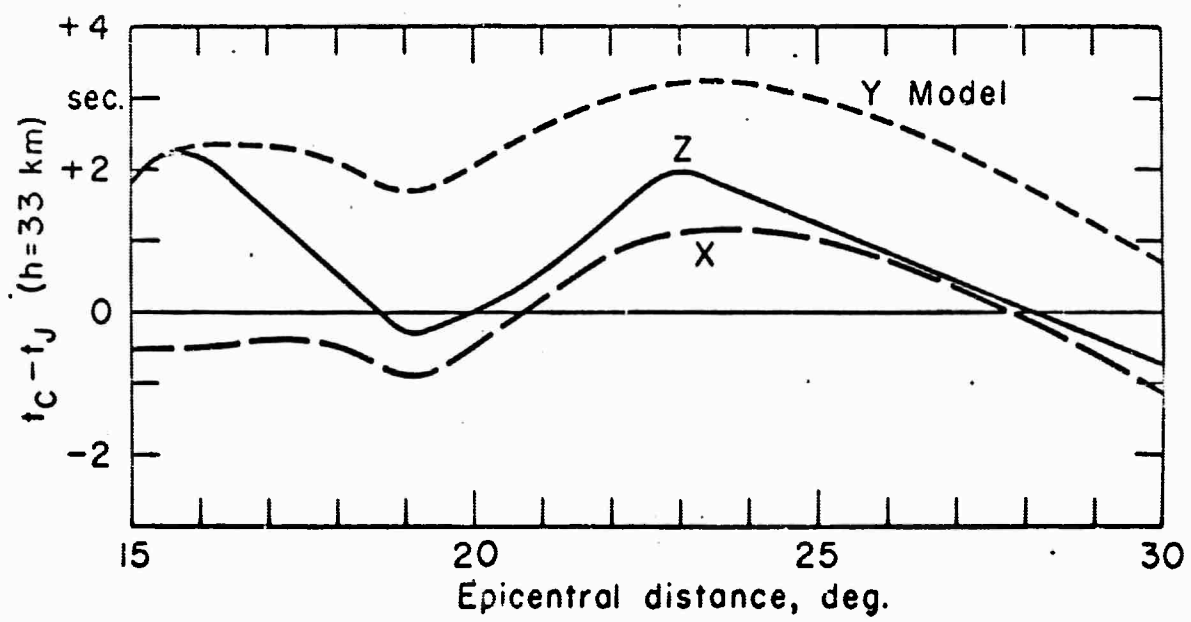
Fig. 5
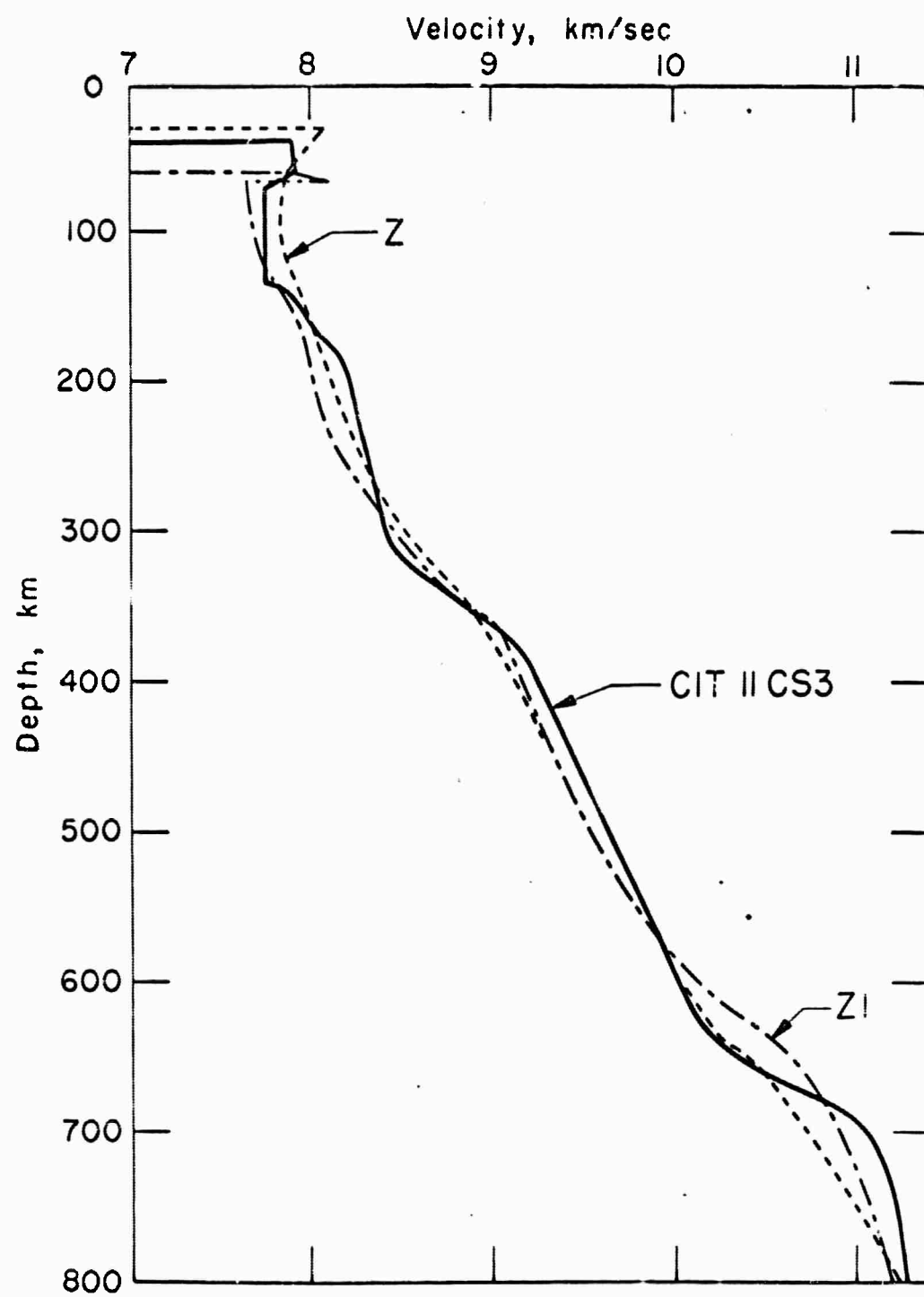
Fig. 6

Fig. 7

Previous Technical Reports in this Series

1. Aki, K., "Further Study of the Mechanism of Circum-Pacific Earthquakes from Rayleigh Waves," Journ. of Geophys. Res. Vol. 65, No. 12, pp. 4165-4172, Dec. 1960.

2. Ben-Menahem, Ari, "Radiation of Seismic Surface-Waves from Simple Models of Fault-Planes, Part 1: Rayleigh Waves."

3. Ben-Menahem, Ari, "Radiation of Seismic Surface-Waves from Simple Models of Fault-Planes, Part II: SH Waves (with application to the G waves)."

4. Cisternas, Armando, "Crustal Structure of the Andes from Rayleigh Wave Dispersion," Bull. Seism. Soc. Am., Vol.51, No. 3, pp. 381-388, July 1961.

5. Phinney, Robert A., "Leaking Modes in the Crustal Waveguide, Part 1. The Oceanic PL Wave," Journ. of Geophys. Res., Vol. 66, No. 5, pp. 1445-1469, May 1961.

6. Aki, K., and Frank Press, "Upper Mantle Structure under Oceans and Continents from Rayleigh Waves," Geophys. Journ. of the Royal Astron. Soc., Vol. 5, No. 4, pp. 292-305, 1961.

7. Press, Frank, David G. Harkrider, and C. A. Seafeldt, "A Fast, Convenient Program for Computation of Surface Wave Dispersion Curves in Multi-layered Media," Bull. Seism. Soc. Am., Vol. 51, No. 4, pp. 495-502, Oct. 1961.

8. Anderson, Don L., "Elastic Wave Propagation in Layered Anisotropic Media," Journ. of Geophys. Res., Vol. 66, No. 9, pp. 2953-2963, Sept. 1961.

9. Press, Frank, Ari Ben-Menahem, and M. Nafi Toksöz,, "Experimental Determination of Earthquake Fault Length and Rupture Velocity," Journ. of Geophys. Res., Vol. 66, No. 10, pp. 3471-3485, Oct. 1961.

10. Ben-Menahem, Ari, "Radiation of Seismic Body Waves from a Finite Moving Source in the Earth," Journ. of Geophys. Res., Vol. 67, No. 1, pp. 345-350, Jan. 1962.

11. Cisternas, Armando, "On Thirlaway's Method for Determination of Focal Depth."

12. Press, Frank, and Charles Archambeau, "Release of Tectonic Strain by Underground Nuclear Explosions," Journ. of Geophys. Res., Vol. 67, No. 1, pp. 337-343, Jan. 1962.

13. Harkrider, David G., and Don Anderson, "Computation of Surface Wave Dispersion for Multilayered Anisotropic Media," Bull. Seism. Soc. Am., Vol. 52, No. 2, pp. 321-332, Apr. 1962.

14. Nordquist, John, "A Special-Purpose Program for Earthquake Location With an Electronic Computer," Bull. Seism. Soc. Am., Vol. 52, No. 2, pp. 431-437, Apr. 1962.

15. Ben-Menahem, Ari, and M. Nafi Toksöz, "Source-Mechanism from Spectra of Long-Period Seismic Surface Waves. 1. The Mongolian Earthquake of December 4, 1957," Journ. of Geophys. Res., Vol. 67, No. 5, pp. 1943-1955, May 1962.

16. Dewart, Gilbert, "Seismic Results for Gnome as Observed by the Caltech Network."

17. Press, Frank, and David Harkrider, "Propagation of Acoustic-Gravity Waves in the Atmosphere," Journ. of Geophys. Res. Vol. 67, No. 10, pp. 3889-3908, Sept. 1962.

18. Smith, Stewart W., "A Reinterpretation of Phase Velocity Data Based on the Gnome Travel Time Curves," Bull. Seism. Soc. Am., Vol. 52, No. 5, pp. 1031-1035, Dec. 1962.

19. Ben-Menahem, Ari, and Armando Cisternas, "The Dynamic Response of an Elastic Half-Space to an Explosion in a Spherical Cavity," Journ. of Math. and Physics, Vol.XL11, No. 2, pp. 112-125, June 1963.

20. Miller, Wayne F., "The Caltech Digital Seismograph," Journ. of Geophys. Res.. Vol. 68, No. 3, pp. 841-847, Feb. 1963.

21. Toksöz, M. Nafi, and Don L. Anderson, "Generalized Two-Dimensional Model Seismology with Application to Anisotropic Earth Models," Journ. of Geophys. Res., Vol. 68, No. 4, pp. 1121-1130, Feb. 15, 1963.

22. Smith, Stewart W., "Generation of Seismic Waves by Underground Explosions and the Collapse of Cavities," Journ. of Geophys. Res., Vol. 68, No. 5, pp. 1477-1483, Mar. 1, 1963.

23. Phinney, Robert A., and Stewart W. Smith, "Processing of Seismic Data From an Automatic Digital Recorder," Bull. Seism. Soc Am., Vol. 53, No. 3, pp. 549-562, April 1963.

24. Nordquist, John M., "Note on Computer Determinations of the Hypocenter of the Sahara Explosion of 1 May 1962."

25. Press, Frank, Gilbert Dewart, and Ralph Gilman, "A Study of Several Diagnostic Techniques for Identifying Earthquakes," Journ. of Geophys. Res., Vol. 68, No. 10, pp. 2909-2928, May 15, 1963.

26. Toksoz, M. Nafi, and Ari Ben-Menahem, "Velocities of Mantle Love and Rayleigh Waves over Multiple Paths, Bull. Seism. Soc. Am., Vol. 53, No. 4, pp. 741-764, July, 1963.

27. Cisternas, Armando, "Precision Determination of Focal Depth and Epicenters of Local Snocks in California," Bull. Seism. Soc. Am., Vol. 53, No. 5, pp. 1075-1083, Oct., 1963.

28. Anderson, Don L., and M. Nafi Toksoz, "Surface Waves on a Spherical Earth. 1. Upper Mantle Structure from Love Waves," Journ. of Geophys. Res., Vol. 68, No. 11, pp. 3483-3500, June 1, 1963.

29. Ben-Menahem, Ari, and M. Nafi Toksoz, "Source-Mechanism from Spectra of Long-Period Surface Waves. 2. The Kamchatka Earthquake of November 4, 1952," Journ. of Geophys. Res., Vol. 68, No. 18, pp. 5207-5222, Sept., 1963.

30. Ben-Menahem, Ari, and M. Nafi Toksoz, "Source-Mechanism from Spectra of Long-Period Seismic Surface Waves. 3. The Alaska Earthquake of July 10, 1958," Bull. of Seism. Soc. of Am., Vol. 53, No. 5, pp. 905-919, Oct., 1963.

31. Toksoz, M. Nafi, "Microseisms and an Attempted Application to Exploration," Geophysics, Vol. XXIX, No. 2, April, 1964.

32. Toksoz, M. Nafi, and Don L. Anderson, "Velocities of Mantle Love and Mantle Rayleigh Waves and the Structure of the Earth's Upper Mantle."

33. Harkrider, D. G., "Propagation of Acoustical Gravity Waves from an Explosive Source in the Atmosphere." Ph.D. Thesis.

34. Harkrider, D. G., "Rayleigh and Love Waves from Sources in a Multilayered Elastic Half-Space." Ph.D. Thesis.

35. Kovach, Robert L., and Don L. Anderson, "Higher Mode Surface Waves and their Bearing on the Structure of the Earth's Mantle," Bull. of Seism. Soc. Am., Vol. 54, No. 1, Feb., 1964.

36. Kovach, Robert L., "Seismic Surface Waves: Some Observations and Recent Developments," Ch. in PHYSICS AND CHEMISTRY OF THE EARTH, Vol. 6 (in press).

37. Gile, William, "A Solid-State Band Pass Filter," Electro-Technology, (in press).

38. Mikumo, T., and K. Aki, "Determination of Local Phase Velocity by Intercomparison of Seismograms from Strain and Pendulum Instruments," Journ. of Geophys Res., Vol. 69, No. 4, Feb. 15, 1964.

39. Aki, Keiiti, "Study of Love and Rayleigh Waves from Earth-quakes with Fault Plane Solutions or with Known Faulting. Part 1. A Phase Difference Method Bason on a New Model of Earthquake Source," Bull. Seism. Soc. Am., Vol 54, No. 2, April, 1964.

40. Aki, Keiiti, "Study of Love and Rayleigh Waves from Earth-quakes with Fault Plane Solutions or with Known Faulting, Part 2. Application of the Phase Difference Method," Bull. Seism. Soc. Am., Vol. 54, No. 2, April, 1964.

41. Aki, Keiiti, "Study of Love and Rayleigh Waves from Earth-quakes with Fault Plane Solutions or with Known Faulting, Part 3. Table of Source Phase Differences Between Rayleigh and Love Waves," Bull. Seism. Soc. Am., Vol. 54, No. 2, April, 1964.

42. Harkrider, David G., "Surface Waves in Multilayered Elastic Media, 1. Rayleigh and Love Waves from Buried Sources in a Multilayered Elastic Half-Space," Bull. Seism. Soc. Am., Vol. 54, No. 2, April, 1964.

43. Anderson, Don L., "Universal Dispersion Tables, 1. Love Waves Across Ocean and Continents on a Spherical Earth," Bull. Seism. Soc. Am., Vol 54, No. 2, pp. 681-726, April, 1964.

44. Aki, Keiiti, "A Note on Surface Waves from the Hardhat Nuclear Explosion," Journ. of Geophys. Res., Vol. 69, No. 6, pp. 1131-1134, March 15, 1964.

45. Anderson, Don L., and Robert L. Kovach, "Attenuation in the Mantle and Rigidity of the Core from Multiply Reflected Core Phases," Proc. of the National Academy of Sciences, Vol. 51, No. 2, pp. 168-172, February, 1964.

46. Anderson, Don L., "Recent Evidence Concerning the Structure of the Upper Mantle from the Dispersion of Long Period Surface Waves," Proc. of the Veslac Upper Mantle Sym., (in press).

47. Toksöz, M. N., and Ari Ben-Menahem, "Excitation of Seismic Surface Waves by Atmospheric Nuclear Explosions," Journ. of Geophys. Res., Vol. 69, No. 8, pp. 1639-1648, April, 1964.

48. Nordquist, John, "A Catalog of Southern California Earth-
     quakes and Associated Electronic Data Processing Programs,"
     Bull. Seism. Soc. Am., Vol. 54, No. 3, 1003-1011, June, 1964.

49. Ben-Menahem, Ari, and David G. Harkrider, "Radiation Patterns
     of Surface Waves from Buried Point Sources in a Flat
     Stratified Earth," Journ. of Geophys. Res., Vol. 69,
     No. 12, 2605-2620, June 15, 1964.

50. Anderson, Don L., and C. B. Archambeau, "The Anelasticity of
     the Earth," Journ. of Geophys. Res., Vol. 69, No. 10
     2071-2084, May 15, 1964.

51. Press, Frank, and Shawn Biehler, "Inferences on Crustal
     Velocities and Densities from P-Delays and Gravity
     Anomalies," Journ. of Geophys. Res., Vol. 69, No. 14,
     2979-2995, July 15, 1964.

52. Shimshoni, Michael, and Stewart W. Smith, "Seismic Signal
     Enhancement with 3-Component Detectors," Geophysics,
     Vol. XXIX, No. 5, 664-671, October, 1964.

53. Ben-Menahem, Ari, "Mode-Ray Duality," Bull. Seism. Soc. Am.,
     Vol. 54, No. 5, Part A, 1315-1321, October, 1964.

54. Toksöz, M. N., A. Ben-Menahem and D. G. Harkrider, "Deter-
     mination of Source Parameters by Amplitude Equalization
     of Seismic Surface Waves. 1. Underground Nuclear
     Explosions," Journ. of Geophys. Res., Vol. 69, No. 20,
     4355-4366, October 15, 1964.

55. Ben-Menahem, Ari, "Spectral Response of an Elastic Sphere
     to Dipolar Point-Sources, Bull. Seism. Soc. Am., (in press).

56. Press, Frank, "Seismic Wave Attenuation in the Crust,"
     (Letter to the Editor), Journ. of Geophys. Res., Vol. 69,
     No. 20, 4417-4418, October 15, 1964.

57. Dewart, Gilbert, and M. Nafi Toksöz, "Crustal Structure in
     East Antarctica from Surface Wave Dispersion," Geophys.
     Journ. (in press)

58. Kovach, Robert L., and Don L. Anderson, "Attenuation of
     Shear Waves in the Upper and Lower Mantle," Bull. Seism.
     Soc. Am., Vol. 54, No. 6, 1855-1864, December, 1964.

59. Smith, Stewart W., "Seismic Digital Data Acquisition
     Systems," Rev. of Geophys., Vol. 3, No. 1, 151-156, Feb. 1965.

60. Harkrider, David G., "Theoretical and Observed Acoustic
     Gravity Waves from Explosive Sources in the Atmosphere,"
     Journ. of Geophys. Res., Vol. 69, No. 24, 5295-5321,
     December 15, 1964.

61. Cisternas, Armando, "Part I - The Radiation of Elastic Waves from a Spherical Cavity in a Half Space. Part II - Precision Determination of Focal Depths and Epicenters of Earthquakes," Ph.D. Thesis.

62. Toksöz, M. Nafi, David G. Harkrider, and Ari Ben-Menahem, "Determination of Source Parameters by Amplitude Equalization of Seismic Surface Waves. 2. Release of Tectonic Strain by Underground Nuclear Explosions and Mechanism of Earthquakes," Journ. of Geophys. Res., Vol. 70, No. 4, 907-922, February 15, 1965.

63. Anderson, Don L., Ari Ben-Menahem, and C. B. Archambeau, "Attenuation of Seismic Energy in the Upper Mantle," Journ. of Geophys. Res., Vol. 70, No. 6, 1441-1448, March 15, 1965.

64. Ben-Menahem, Ari, Stewart W. Smith, and Ta-Liang Teng, "A Procedure for Source Studies from Spectrum of Long-Period Seismic Body Waves," Bull. Seism. Soc. Am., (in press).

65. Alexander, Shelton S., "Methods of Mode Separation of Seismic Surface Waves".

66. Thrower, E. N., and D. G. Harkrider, "A Note on the Existence Maxima and Minima on Phase Velocity Curves," Bull. Seism. Soc. Am., (in press).

67. Allen, C. R., P. St. Amand, C. F. Richter, and J. M. Nordquist, "Relationship Between Seismicity and Geologic Structure in the Southern California Region," Journ. of Geophys. Res., (in press).

68. Press, Frank, "Dimensions of the Source Region for Small Shallow Earthquakes," Proc. Vesiac Conf., La Jolla, Calif., 1965.

69. Duda, S., "Regional Seismicity and Seismic Wave Propagation from Records at the Tonto Forest Seismological Observatory. Payson, Arizona," Proc. Roy. Soc., (in press).

70. Teng, Ta-Liang, "Amplitudes of Body Waves," Bull. Seism. Soc. Am., (in press)

71. Ben-Menahem, Ari, "Observed Attenuation and Q Values of Seismic Surface Waves in the Upper Mantle," Journ. Geophys. Res., (in press).

72. Wu, Francis, T., A. Ben-Menahem, "Surface Wave Radiation Pattern and Source Mechanism of the September 1, 1962 Iran Earthquake," Journ. Geophys. Res., (in press).

73. Ben-Menahem, A., "Summation of Certain Legendre Series and Related Difference Equations," Journ. Geophys. Res., (in press).

74. Ben-Menahem, Ari, "Source Studies from Isolated Seismic Signals" Proc. Vesiac Conf., La Jolla, Calif., 1965.

75. Niazi, Mansour, and Don L. Anderson, "Upper Mantle Structure of Western North America from Apparent Velocities of P Waves," Journ. of Geophys. Res., (in press).